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# OPAL: Network for the Detection of Stratospheric Change Ozone Profiler Assessment at Lauder, New Zealand

## 2. Intercomparison of Revised Results

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**Abstract.** Following a blind intercomparison of ozone profiling instruments in the Network for the Detection of Stratospheric Change at Lauder, New Zealand, revisions to the analyses were made resulting in a new data set. This paper compares the revised results from two differential absorption lidars (RIVM and GSFC), a microwave radiometer (Millitech/LaRC), and electrochemical concentration cell (ECC) balloon sondes (NIWA). In general, the results are substantially improved compared to the earlier blind intercomparison. The level of agreement was similar both for single profiles and for the campaign average profile and was approximately 5% for the lidars and the sondes over the altitude range from 15 to 42 km (32 km for sondes). The revised microwave data show a bias of 5–10% high in the region from 22 to 42 km. Starting at 42 km, the lidar errors increase significantly, and comparisons of the microwave results were not possible above this altitude.

## 1. Introduction

The Ozone Profiler Assessment at Lauder (OPAL) was carried out from April 15 to 29, 1995, at New Zealand National Institute of Water and Atmosphere (NIWA) atmospheric research station (45.05°S, 169.68°E). This intercomparison campaign was carried out following the protocols established by the Network for the Detection of Stratospheric Change (NDSC) for the validation of instruments [NDSC, 1998]. Results from the first phase of the campaign, which was carried out as a blind intercomparison, have been presented by *McDermid et al.* [this issue]. Following the blind campaign, the investigators had an opportunity to study their results and the

comparisons with other instruments in detail. For all of the Lauder instruments the investigators did find some kind of problem, either hardware or software related, and all groups submitted revised data for consideration. To be accepted into the revised assessment, the problems and changes made had to be fully documented and justified. In the case of changes to the analysis routines it was expected that all previously acquired data would be reanalyzed with the new method, not just the OPAL data.

This paper compares the revised results submitted for the RIVM DIAL system, the Millitech microwave radiometer, the NIWA electrochemical concentration sondes (ECC), and the STROZ-LITE mobile DIAL system from the Goddard Space Flight Center (GSFC). For a brief description of these instruments and for a more detailed description of the OPAL campaign the reader is referred to part 1 of *McDermid et al.* [this issue].

## 2. Data Revisions

### 2.1. RIVM DIAL Revisions

At the time of the OPAL campaign the algorithms to extract ozone profiles from the lidar returns were still under development. Continuation of this development has led to improvements in the treatment of high-signal level nonlinearity corrections (pulse-pile-up errors) and the implementation of a correction procedure for signal-induced noise (SIN) [Donovan *et al.*, 1993]. The high-signal level nonlinearity correction was determined from dedicated measurements using neutral density filters to vary the signal levels. Typically, this correction influences the ozone profiles at altitudes below 18 km for the near channels and at 23–30 km for the far channels. In this case, the nonlinearity correction is found to lower the derived ozone density. The SIN corrections are performed by subtracting an extrapolated exponential background fit from the mea-

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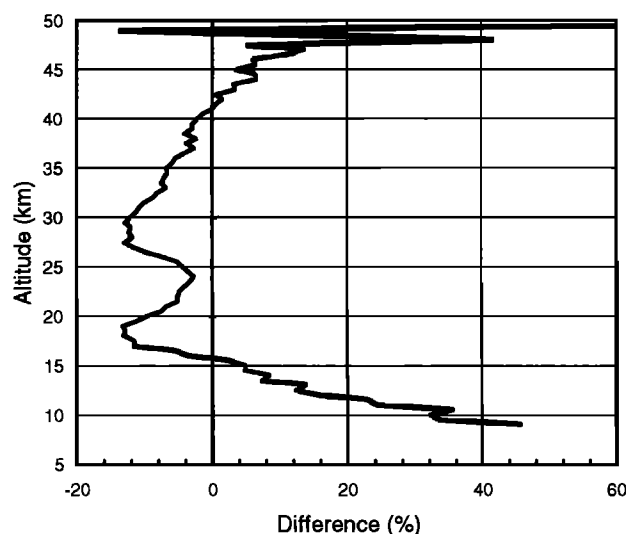
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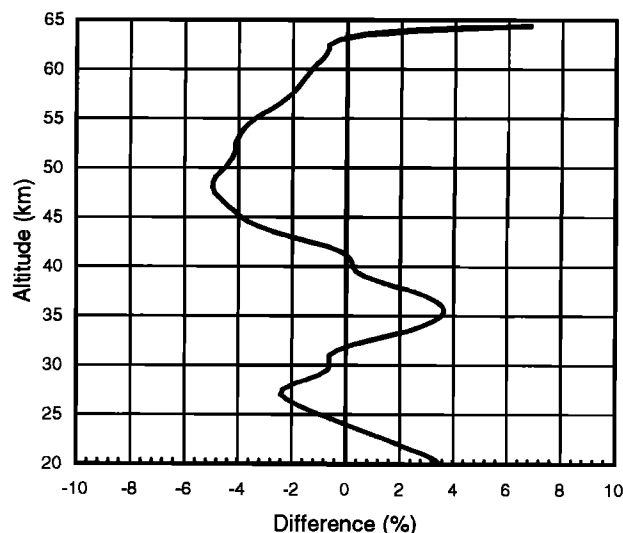
<sup>15</sup>Now at GATS, Inc., Hampton, Virginia.



**Figure 1.** Difference between the blind and the revised mean RIVM lidar profiles (revised-blind/revised).

sured signals (fit domain depending on signal levels). The SIN correction increases the ozone density at high altitudes, typically above 20 km in the near channels and above 35 km in the far channels.

Several other aspects of the RIVM ozone algorithm were investigated. The altitude registration has been improved resulting in a profile shift of  $-41$  m for profiles measured using  $1 \mu\text{s}$  time bins (OPAL April 15–17) and  $-266$  m for profiles using  $2 \mu\text{s}$  time bins (April 20–29). A programming error resulting in a constant rather than decreasing Rayleigh extinction correction at altitudes above 30 km has been rectified. This error caused spurious negative concentrations of ozone above 30 km. The difference between the mean profiles from the blind set and the revised results is shown in Figure 1. These differences are quite substantial over most of the profile.



**Figure 2.** Difference between the blind and the revised mean Millitech microwave profiles (revised-blind/revised).

## 2.2. Millitech/LaRC Microwave Radiometer Revisions

The microwave data were reprocessed in a manner consistent with the current, larger data set for the microwave radiometer at Lauder. Two minor modifications were made to the calibration procedure to better adapt it to the prevailing conditions at Lauder. These changes, which are described in detail below, generally reduce the measured ozone values by a few percent compared to the blind data, as shown in Figure 2. One of the changes to the calibration involved choosing climatologically appropriate temperatures for the isothermal model troposphere that is used to determine the tropospheric attenuation of the ozone signal, based on sonde measurements of the temperature and humidity profile. Some atypically strong nighttime temperature inversions were observed at the time of the OPAL campaign, and if these profiles were taken as typical for the OPAL period instead of the climatological average applicable to the larger data set, the measured ozone would decrease by about an additional 2%. The errors associated with the revised OPAL data are given in Table 1 and were calculated by the methods described by Connor *et al.* [1995].

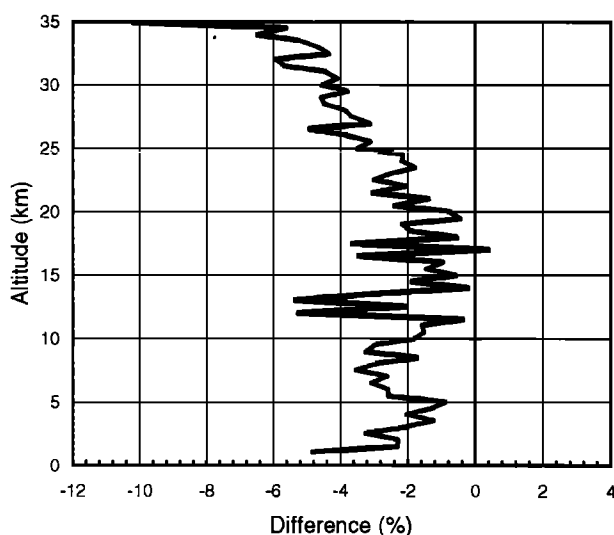
The first modification involved the derivation of the opacity of the troposphere from the measured intensity of its thermal radiation. It was discovered that the blind results exhibited small diurnal variations at altitudes below 50 km where none were expected, particularly at the time of the campaign. These were traced to differences between the daytime and the nighttime tropospheric temperature profiles (temperature inversions are frequently observed at night) which were not accounted for in the calibration. The calibration procedure uses an analytically solvable isothermal model atmosphere (described by Parrish *et al.* [1992]) to relate the tropospheric opacity to the measured intensity of the tropospheric thermal radiation. This is necessary because data on the true absorption profile are not continuously available. For the blind results, the temperature of the model atmosphere was taken to be a fixed amount less than the measured surface temperature at all seasons and times of day. A study using available temperature and humidity profiles recorded by ECC ozonesonde flights was subsequently made to determine the optimum temperature offsets (in a climatological sense) to use in this model. The temperature offset is defined as the difference between the measured air temperature near the ground and the temperature assigned to the isothermal model atmosphere. An optimum offset is one which produces a tropospheric thermal radiation intensity from the isothermal model that equals the intensity calculated with full radiative transfer for a given absorption profile, when the opacity entered into the model is the value calculated from the profile. Optimum temperature offsets versus day number were calculated for each of the available sonde temperature and humidity profiles and were grouped into daytime and nighttime sets. Sinusoidal functions having a 1 year period were fitted to these sets, and these

**Table 1.** Precision and Accuracy for Microwave Mixing Ratio Measurements During OPAL

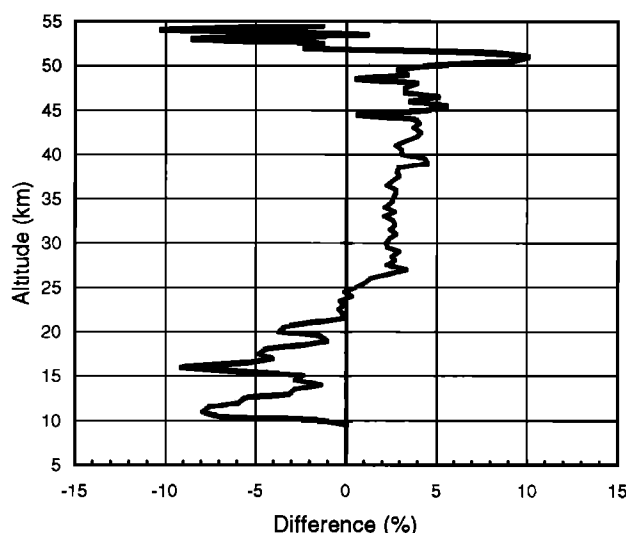
P, hPa	Approx. Z, km	Precision, %	Accuracy, %
56	20	4	6
12	30	4	6
3	40	5	8
0.8	50	5	8

functions were applied to determine the temperatures to be used in the isothermal model when reducing all the Lauder data, including the OPAL data. The peak-to-peak amplitude of the nighttime function corresponds to about a 5% variation in the ozone measurement calibration; that of the daytime function corresponds to about a 2% variation. The rms of the residuals corresponds to about a 2% variation in the calibration for both sets. This uncertainty is small compared to the 4% uncertainty in the tropospheric opacity measurement given in the error analysis discussed by Connor *et al.* [1995]. Therefore it was not found necessary to increase the uncertainty estimates given in that paper to accommodate the new information obtained in this analysis.

The second adjustment involved the measurement of the difference between the true elevation angle of the centroid of the signal beam and the angle reported by the encoder on the instrument. For reducing the blind data, this offset was measured by scanning the beam past a calibration target, of which the position has been determined with respect to the instrument by a survey. However, a later survey made in 1996 gave a different target position than the original 1992 survey, most likely because of settling and/or heaving of the instrument shelter or calibration target foundations. The net difference was an amount that would affect the measured ozone values by 3.5%. In an attempt to eliminate uncertainty from this source, the elevation angle offset was determined by making it an adjustable parameter in the least squares fitting routine that calculates the opacity from the tropospheric signal intensities measured at five elevation angles between 10° and 28°. If the offset value is not optimum, the fit at the extremes of the elevation angle range will be degraded. This technique was used in reducing the revised data. It is estimated that the error component due to use of this technique is 4%, and this error is classified as a component of the accuracy of the measurement because it is unlikely that the elevation calibration changed during the short period of the campaign. Multiyear comparisons between SAGE II and Lauder ECC ozonesonde results with microwave data reduced by using both techniques described above are entirely consistent with this estimate.



**Figure 3.** Difference between the blind and the revised mean NIWA ECC ozonesonde profiles (revised-blind/revised).



**Figure 4.** Difference between the blind and the revised GSFC lidar results.

### 2.3. NIWA ECC Sonde Revisions

Revisions to the ozonesonde data were concentrated in two main areas. First, the geopotential heights were recalculated after a small error was found in the data processing software. At the same time, the algorithm was extended to include the effects of water vapor in this calculation. Secondly, all ozonesonde partial pressures were multiplied by 0.9743 to account for the change in the ozone absorption coefficients applicable to the Dobson spectrophotometer retrieval of total ozone on which the ozonesonde measurements were originally based. The formula used to convert the current measured by the ECC to ozone partial pressure includes a “constant” that was originally determined by ensuring that the integrated ozone profile from the sonde matched a simultaneous Dobson spectrophotometer measurement. The Dobson instruments and network previously used the ozone absorption coefficient from Vigoroux [1953, 1967] but recently changed [Komhyr *et al.*, 1993] to the newer values reported by Bass and Paur [1985]. Rather than changing the constant in the sonde analysis, the ozone partial pressures are multiplied by 0.9743, which is the average change from the old to the new Dobson readings. However, the ozone partial pressures measured by the ozonesonde are not normalized to an independent total column ozone measurement. The lidars have always used the Bass and Paur absorption coefficients.

The difference between the mean profile, from averaging all nine flights, in the blind and revised data sets is shown in Figure 3. The effect of the change to the ozone absorption coefficient is a constant  $-2.6\%$  over the complete profile.

### 2.4. GSFC DIAL Revisions

The only change to the GSFC lidar results stems from the discovery of a  $1.25 \mu\text{s}$  timing error in the data acquisition system. This results in a 187 m offset in the revised data compared to the blind set. The ozone values are unchanged, but the entire profile is moved up 187 m. The differences between the GSFC blind and revised results are summarized in Figure 4.

### 3. Revised Results

#### 3.1. Campaign Average Profiles

As in the blind intercomparison, a mean profile from all measurements made by each instrument during the campaign was generated, as shown in Plate 1. It was decided not to include the SAGE II results in the revised intercomparison since the SAGE profile in the blind intercomparison did not agree well with the OPAL instruments and did not assist in determining the true or best ozone profile to which the instruments should be compared. To see the effects of the revisions, Plates 1 and 2 can be compared with Plates 3 and 6 of part 1 [McDermid *et al.*, this issue].

Considering each instrument in turn, it can first be seen (Plates 1 and 2a) that the RIVM lidar measurements have been improved at the top of the profile, now agreeing within 10% with the GSFC lidar and the microwave radiometer at 45 km compared to only 40 km for the blind results. In the region from 15 to 45 km the RIVM lidar and GSFC lidar agreement is improved, and for most of this range it is within  $\sim 5\%$ , increasing to  $\sim 10\%$  at the upper and lower ends. The agreement with the ECC sonde is also improved and is better than 10% in the region from 15 to 35 km. However, below 15 km the agreement with the GSFC lidar and the ECC sondes is considerably worse than in the blind intercomparison and increases steadily to  $\sim 50\%$  at 10 km, where it previously agreed to better than 10% with the GSFC lidar.

The revised microwave radiometer results now appear to show a positive bias, in the 20–45 km altitude region, compared to all of the other instruments (Plates 1 and 2b). The shape of the difference curves is improved in the sense that the differences to the other instruments is now almost constant where there was a sinusoidal or sigmoid shape for the blind differences, but there is a bias of as much as 10% at 30 km.

Although the ozone amounts reported in the microwave revised mean profile are slightly less than in the corresponding blind profile over most of the altitude range, they are still typically 5–10% higher than the revised amounts reported by the other instruments. This bias is not consistent with results obtained in two other intercomparison campaigns, in which the microwave measurements were well grouped with the others. In the STOIC campaign [Margitan *et al.*, 1995] the present microwave instrument was compared to lidars, sondes, SAGE II, and others at Table Mountain, California; in the MLO3 campaign [McPeters *et al.*, 1996], another, essentially identical Millitech microwave instrument, was compared to lidars, sondes, and SAGE II at Mauna Loa, Hawaii. At these high, dry sites, the tropospheric attenuation of the stratospheric ozone signal is substantially less than it is at Lauder; this is the major difference between the microwave measurements at Lauder and those at the other sites. The sensitivity of the microwave instrument is such that error due to receiver noise is still a small part of the total error budget, despite the weaker signal. However, the microwave measurement is more sensitive to the details of the tropospheric temperature and water vapor profiles there. The technique described in section 2 and used in determining the tropospheric attenuation in the calibration of the revised data was intended to reduce sensitivity to seasonal variations of these profiles. This technique was not used in the other two campaigns. Ozone values from these campaigns

would have been slightly, not more than 1.5%, larger if it had been used. As discussed in section 2, the microwave ozone values at Lauder would decrease slightly, not more than 2%, if only the tropospheric temperature and water vapor profiles obtained during the campaign had been used in the data reduction instead of a seasonal average. These two small effects would make the results of the OPAL campaign a little more consistent with the others but would not completely eliminate the inconsistency. The cause of the remaining inconsistency is presently not understood.

The ECC sonde and GSFC lidar results (Plates 1, 2c, and 2d) appear to have merged and agree almost perfectly from 20 to 30 km. Above 30 km the sonde measurements start to be slightly low, which is contrary to some other intercomparisons and sonde performance issues in this altitude range [McPeters *et al.*, 1996]. Between 15 and 20 km there are some deviations which are most likely due to the much higher spatial resolution of the sondes compared to the lidars. Below 15 km the lidars and the sondes show significant disagreement. In this region the lidar errors increase rapidly due to uncertainties in the Rayleigh extinction correction, but the sonde should be performing optimally.

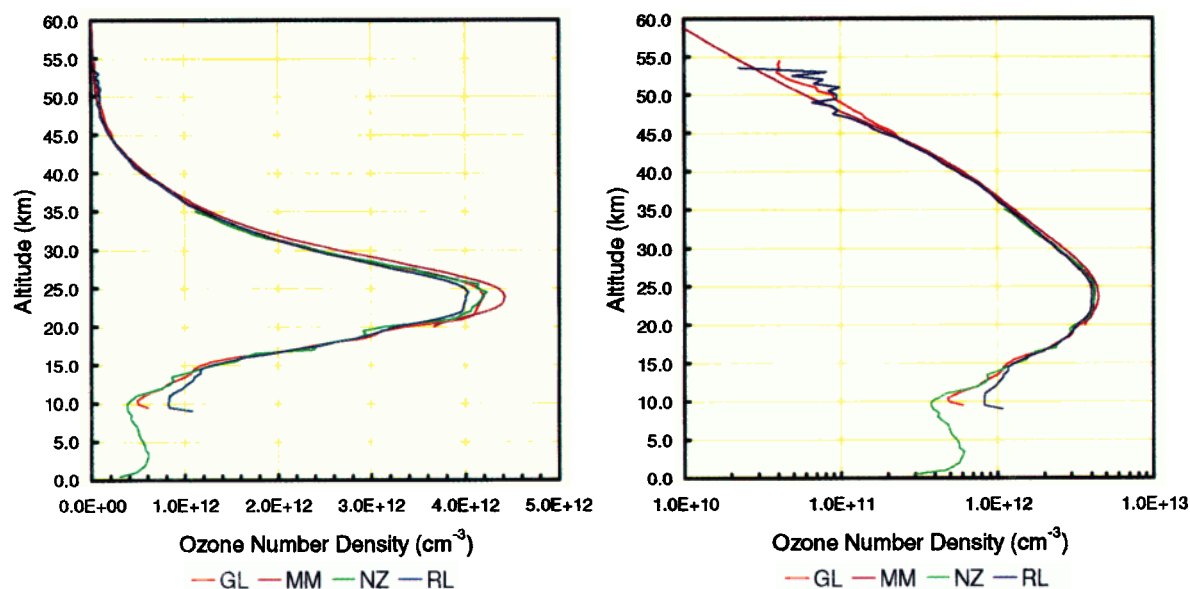
#### 3.2. Single Profiles, April 20, 1995

An example of the intercomparison of single profiles, using results obtained on April 20, 1995, is shown in Plates 3 and 4. To relate the revised results to those from the blind campaign, Plates 3 and 4 should be compared with Plates 7 and 9 of part 1 [McDermid *et al.*, this issue]. With the exception of the microwave results the agreement is improved significantly compared to the blind intercomparison. Even for the microwave results the agreement is much better, in the sense that the difference curve is essentially a straight line with a constant bias. The agreement for these single profiles is similar and as good as is seen for the campaign average profiles.

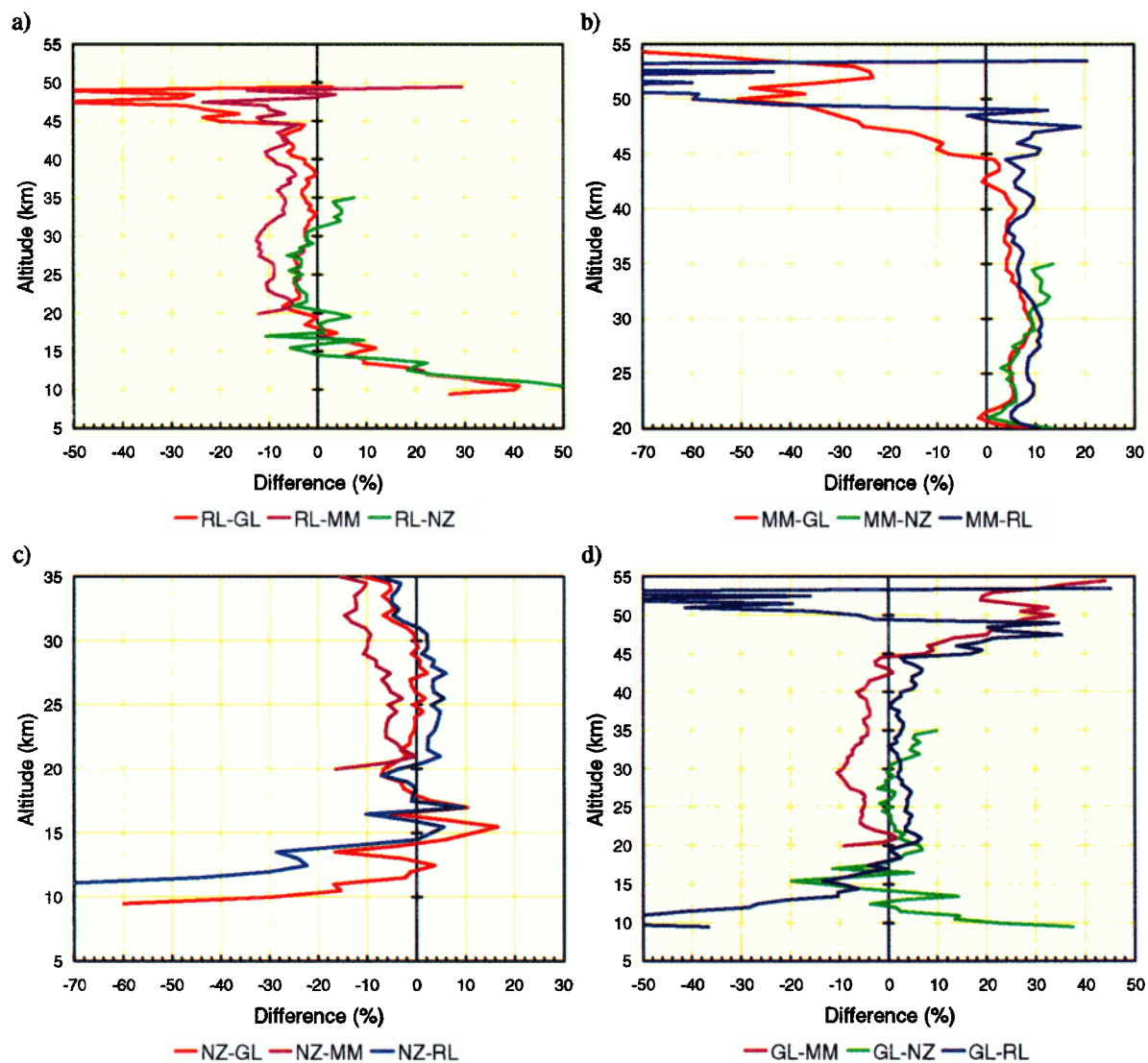
Except for a dip observed by the RIVM lidar near the ozone maximum at  $\sim 22$  km, the two lidars and the ECC sondes agree within 5% from approximately 15 to 32 km altitude. From 32 to 35 km the maximum altitude for the sonde, the difference between the ECC and the lidars, increases to about 10% with the sonde measurement being lower. Good agreement between the lidars continues to  $\sim 42$  km. While the microwave results agree with the other instruments at 20 km, the lowest altitude for the microwave measurement, the differences increase to an approximately constant 10% from 23 to 42 km. Above this altitude the lidar measurements are not good, and there is therefore nothing to compare to in this region.

### 4. Conclusions

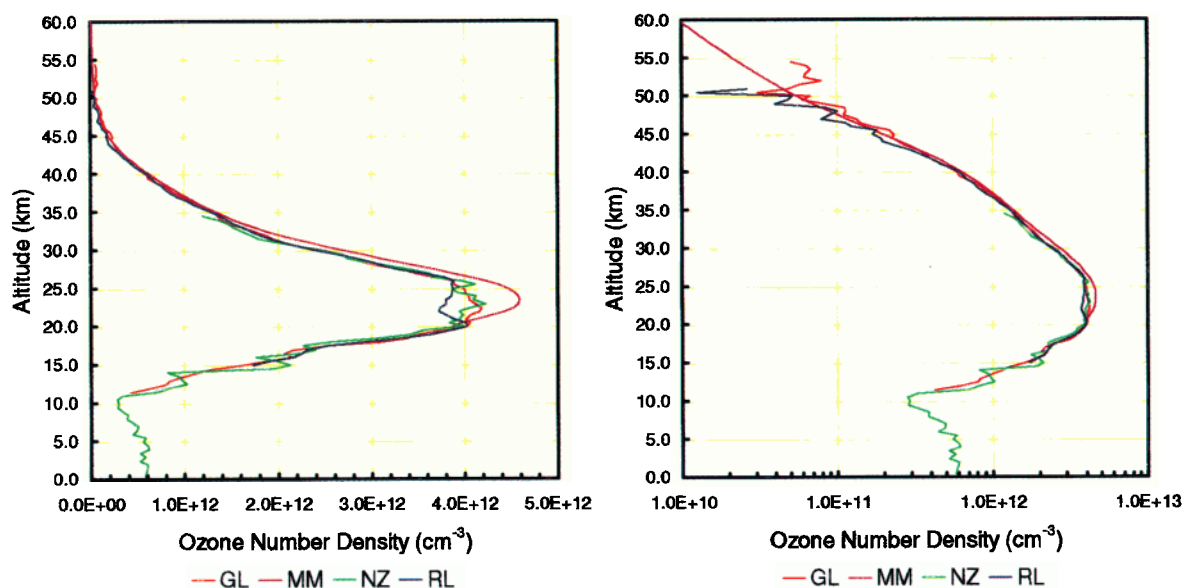
In general, the revisions to the OPAL data set improved the agreement between instruments. The apparent 5–10% bias between the microwave and the other profiles measured during the OPAL campaign was not observed in other, similar campaigns. The cause of most of this bias is not presently understood; some of it may be attributed to the higher tropospheric attenuation at the Lauder site, compared to the others, and the details of the techniques used to measure the attenuation.



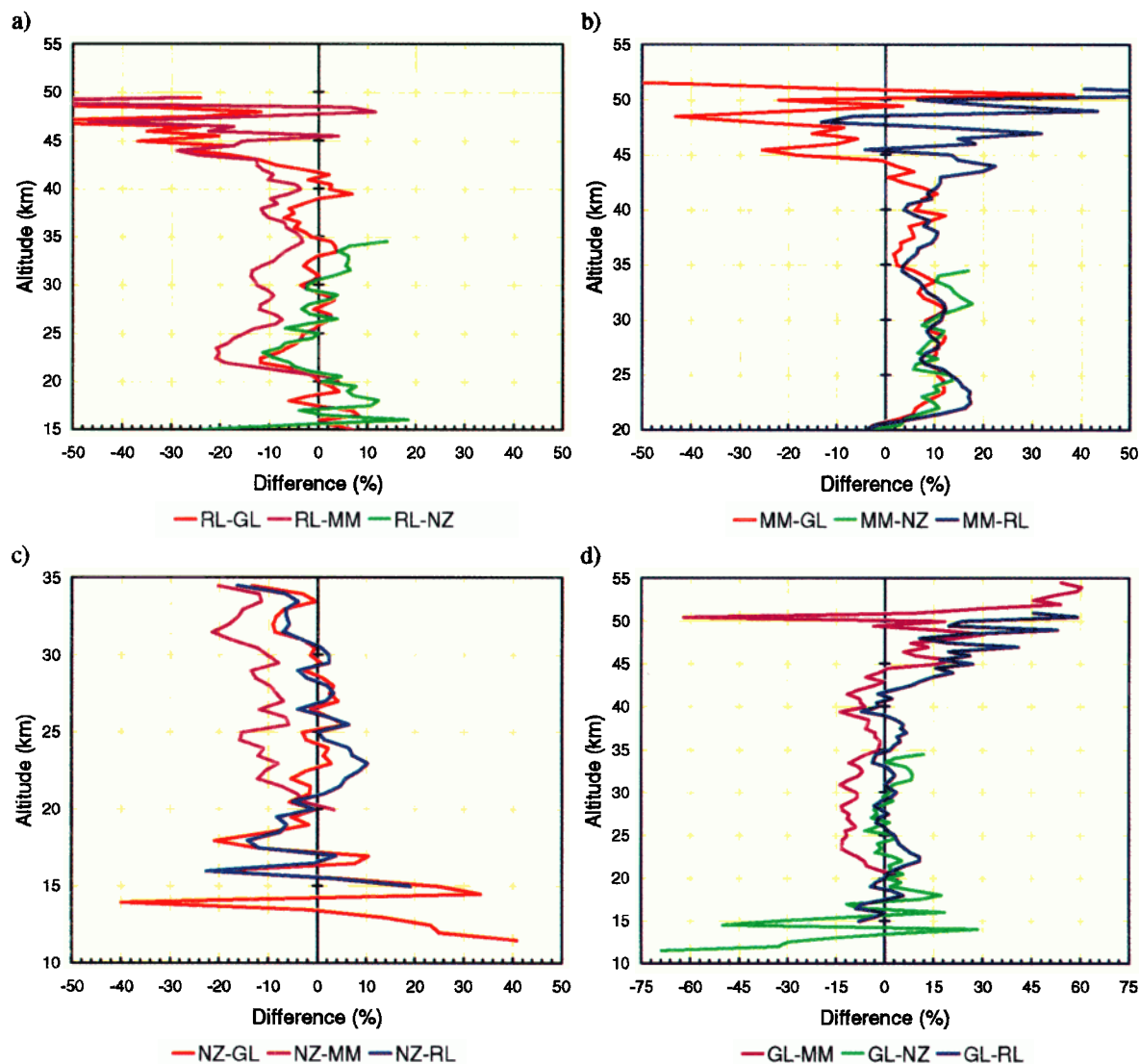
**Plate 1.** Revised results: Ozone profiles averaged over the entire OPAL campaign period for each instrument.



**Plate 2.** Differences between the revised mean profile for each instrument and all other revised mean profiles. (a) (RL-X)/RL, (b) (MM-X)/MM, (c) (NZ-X)/NZ, and (d) (GL-X)/GL.



**Plate 3.** Individual revised ozone profiles for April 20, 1995.



**Plate 4.** Difference between the RIVM (RL) lidar-revised profile and all other revised profiles for April 20, 1995. (a) (RL-X)/RL, (b) (MM-X)/MM, (c) (NZ-X)/NZ, and (d) (GL-X)/GL.

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